AN ELECTROMECHANICAL CAPACITOR FOR ENERGY TRANSFER*

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Summary

Inductive energy transfer between two magnets can be achieved with almost 100% efficiency with a transfer capacitor. However, the bulk and cost will be high, and reliability low if conventional capacitors are used. A homopolar machine, used as a capacitor, will be compact and economical. A homopolar machine was designed with counter-rotating copper disks completely immersed in a liquid metal (NaK-78) to work as a pulse capacitor. Absence of solid-brush collectors minimized wear and frictional losses. Wetting of the copper disks throughout the periphery by the liquid metal minimized the resistive losses at the collector interface. A liquid-metal collector would, however, introduce hydrodynamic and magnetohydrodynamic losses. The selected liquid metal, e.g., NaK-78 will produce the lowest of such losses among the available liquid metals. An electromechanical capacitor of this design was tested at various dc magnetic fields. Its measured capacitance was about 100 farads at a dc magnetic field of 1.15 tesla.

Introduction

Inductive energy transfer between two magnets can be achieved with almost 100% efficiency with a transfer capacitor (Fig. 1). However, the volume and cost will be high, and reliability low if conventional capacitors are used. A homopolar machine, used as a transfer capacitor, will be compact and economical.

A homopolar machine can be considered to be an energy-storage device. It would be spun up by a turbine, or charged as a homopolar motor from a charging supply, and then discharged to a load. An alternate use which we propose, is to employ the homopolar machine as a transfer capacitor, i.e., the electromechanical capacitor (EMC), between an inductive energy store and an inductive load. Initially, the rotor would be at rest with the dc magnetic field energized. During energy transfer, it would be spun up and spun down again, all in a time period of a few milliseconds. Since rotation persists for only a very short time, the brushes and bearings could be more frictional than would be permissible in a continuously running machine.

The operation of the homopolar machine is based on the Faraday disk. A metallic disk, mounted on bearings, will rotate around its axis when a magnetic field is applied in a direction perpendicular to its surface and a current is passed through it in a radial direction via brush contacts. The voltage generated between the brushes by the rotation of the disk is given by

$$V = \int_{r_1}^{r_2} \nu \times B \cdot dr$$

$$= \frac{\omega B}{2} \cdot (r_2^2 - r_1^2) \quad , \qquad (1)$$

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where V = generated voltage across the disk, V,
ν = peripheral speed of the disk, m/s,
B = magnetic field, T,
ω = rotational velocity of the disk, rad/s, and
r_1, r_2 = radial distances of the brush contacts from the axis, m.

The effective capacitance of the homopolar machine can be derived by equating the kinetic energy of the disk with the electrical energy stored in the homopolar machine. Thus,

$$C = I(\omega/V)^2 \quad . \qquad (2a)$$

Substituting for V from eq. (1),

$$C = \frac{4I}{B^2(r_2^2 - r_1^2)^2} \quad , \qquad (2b)$$

where C = capacitance of the machine, F, and
I = moment of inertia of the disk, kg - m^2.

Los Alamos Design of Electromechanical Capacitor

Description of the Device

The conceptual design of the electromechanical capacitor (EMC) is shown in Fig. 2. It consists of two counter-rotating copper disks electrically connected in series. The disks are 20 cm in radius, 0.48 cm thick, and completely immersed in the liquid metal NaK (an alloy of sodium and potassium). The current paths are shown by arrows in Fig. 2. Sheets of insulation are inserted between the two disks and between the disks and the stators to prevent short circuiting of the current by the liquid metal. Contact is made to the outside of the disks and from disk to stator and disk to disk by the liquid metal. Complete flooding with liquid metal prevents interference with brush contact by hydrodynamic and magnetic forces.

Liquid-Metal Brushes[1,2]

Liquid metal bridging the gap between the rotating disks and the stationary current-collecting rings shows considerable promise. Liquid metals offer the advantage of high current density, low loss, less maintenance and saving in space and size.

Mercury, gallium-indium alloy, and an alloy of sodium and 78% by weight of potassium (NaK-78) are liquid at room temperature. Therefore, these metals could be used as liquid-metal brushes. Their pertinent properties are shown in Table I.

Two important criteria are that the rotor/stator slip-ring surfaces should be wetted by the liquid metal, and that any chemical reaction between the surface and the liquid should be negligible during the life of the machine. However, the ability to wet may

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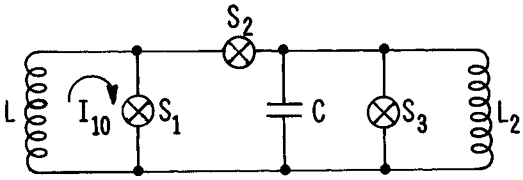


Fig. 1. Circuit for transferring magnetic energy by transfer capacitor. Energy transfer is initiated by opening switch S_1 and closing switch S_2. Switch S_3 is closed at the end of energy transfer.

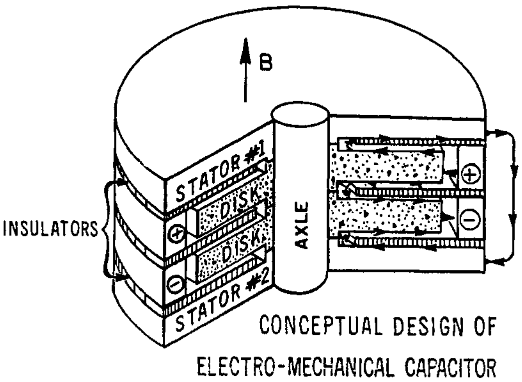


Fig. 2. Conceptual drawing of electromechanical capacitor (EMC).

be related to the compatibility of metals as indicated by binary-phase diagrams, so that wetting and freedom from attack may to some extent be conflicting requirements.

Low density and low viscosity are desirable to minimize hydrodynamic losses, and high electrical conductivity will reduce ohmic losses. As evident from Table I, NaK is the most suitable liquid metal for this application.

Materials Compatibility[3-6]

NaK is a highly reactive liquid metal, and consequently is incompatible with many materials - metals and nonmetals. The EMC was manufactured with copper because of its low electrical resistivity and compatibility with NaK. Nitrile was used for O-rings and gaskets, and polycarbonate sheets were used in the EMC as dielectric material. Although copper is compatible with NaK, even a micron-thick copper oxide layer would prevent NaK from wetting the copper surface. To enhance wetting, chemically cleaned copper surface was coated with 25.4-μm thick silver. NaK dissolves silver and wets the copper surface. Silver was thus used as a sacrificial material.

Installation of EMC

Alkali metals such as NaK may catch fire spontaneously in air. They also react violently with water, liberating and igniting hydrogen. Therefore, they must be handled under a dry inert gas such as argon. The polycarbonate dielectric sheets and the nitrile O-rings and gaskets were cleaned with Alconox™ solution and either acetone or methyl alcohol, rinsed in water, dried and packaged in polyethylene bags before installation.

The cleanliness and compatibility of the filling system are also important. Stainless steel was used for the filling system because NaK wets stainless steel easily and thus flows better. The whole system i.e., the EMC and the filling system, must be leak tight; otherwise air will diffuse through and form oxides of Na and K which are solid. Welded joints and compression-fitting joints were used in the system. Bellows-sealed valves were used for definite closure of the valves. The stainless steel piping and fittings were also chemically cleaned.

A schematic of the filling system is shown in Fig. 3, and its photograph in Fig. 4. The filling system and the EMC were evacuated for 24 hours before the cover gas line was pressurized with argon gas and the valves 1 and 2 of the NaK container were opened. Once the EMC was completely filled and the NaK reservoir half-filled with NaK, the EMC and the NaK reservoir were disconnected from the filling system and installed inside the water-cooled dc magnet (Fig. 5).

Tests on the EMC

The circuit for testing the EMC is shown in Fig. 6. A bank of 280-mF electrolytic capacitors was discharged into the EMC through an ignitron and a 10:1 step-down transformer. Tests were performed at various levels of dc magnetic field and pulse current to the EMC. The following were measured:

1. Current through the dc magnet,
2. EMC rotor pulse current,
3. Voltage across the EMC, and
4. EMC rotor speed.

The dc magnetic field was calculated from the measured value of the magnet current. The calculated value was previously checked by actual measurement of the magnetic field by a gaussmeter. The pulse current was measured with a Rogowski flux coil, and an integrator, and displayed on a dual-beam cathode ray oscilloscope. The EMC voltage was measured with a differential preamplifier. The rotor speed was measured with a rotary encoder having 1000 line pairs and a 100-kHz frequency-to-voltage converter. Figure 7 shows the typical oscillograms of a test.

Discussion

The voltage across the EMC is given by

$$V = \frac{Q}{C} = \frac{\int i dt}{C} , \quad (3)$$

where V = voltage across the EMC, V
Q = charge injected into the EMC, C,
i = charging current, A, and
C = effective capacitance of the EMC, F.

The voltage across the EMC will be zero at the beginning of the charge, and maximum at the end when the current is zero. Figure 7 shows that the voltage across the EMC is initially zero, and it rises as the current falls to zero. However, the voltage attains its peak before the current goes to zero. This indicates that the EMC has a loss component.

If the time to peak of the pulse current is significantly shorter than the time to fall back to zero, then the current wave can be approximated as

TABLE I

PERTINENT PROPERTIES OF Hg, GaIn and NaK

	Hg	76% Ga 24% In	22% Na 78% K
Electrical resistivity, $\mu\Omega m$	1.04	0.29	0.35 - 0.50
Density, g/cc	13.55	6.30	0.8 - 0.9 at 100°C
Viscosity, kg/m-s	1.2×10^{-3}	1.47×10^{-3}	0.4×10^{-3}-0.5×10^{-3}
Melting point, °C	-38.9	15.7	-12.5
Surface tension, dyn/cm	400-500	-	115 at 100°C

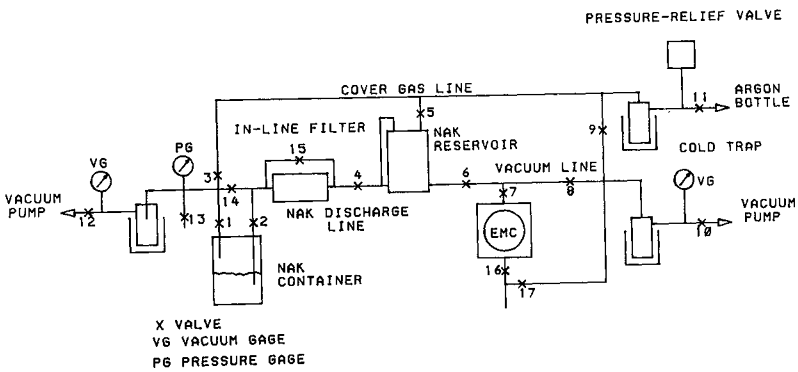


Fig. 3. Schematic of the NaK-filling system.

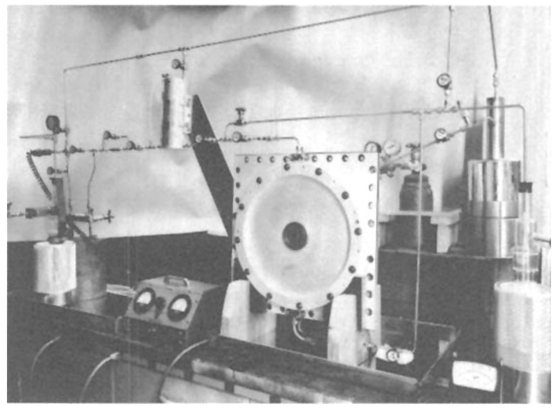
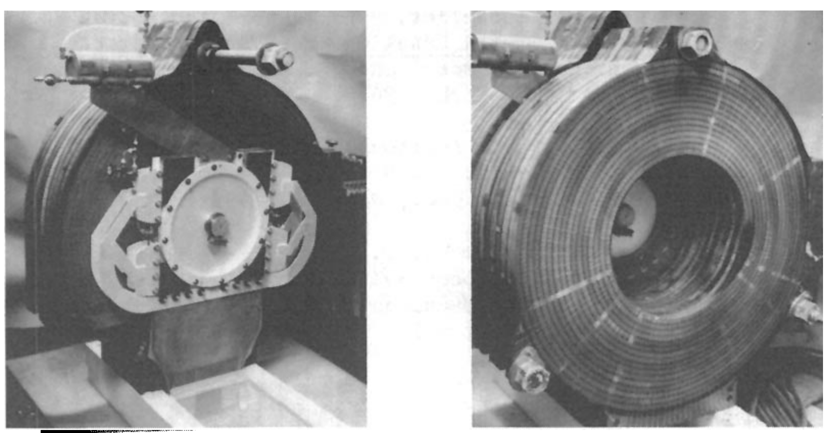


Fig. 4. Photograph of NaK-filling system.



(a) (b)

Fig. 5. Installation of EMC in dc magnet.
(a) magnet half assembled.
(b) fully assembled system.

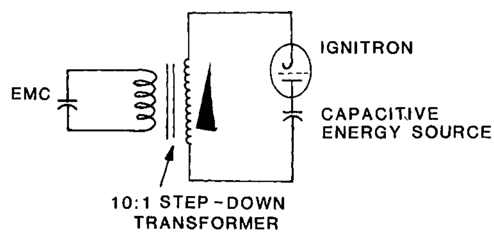


Fig. 6. Schematic of EMC test circuit.

$$I(t) = I_{cp}(1 - t/t_{co}) \quad , \tag{4}$$

where I_{cp} = current peak, and
t_{co} = time for current to fall back to zero.

It can be shown that the time interval between the voltage peak and the current zero is

$$t_{co} - t_{vp} = RC \tag{5}$$

where t_{vp} = time at voltage peak, and
R = effective series resistance of the EMC.

The effective capacitance of the EMC calculated from eq. (2b) is 103 F at B = 1.15 T. It was verified by eq. (3) and Fig. 7 to be 107 F. The effective resistance, as calculated from eq. (5) was 90 $\mu\Omega$.

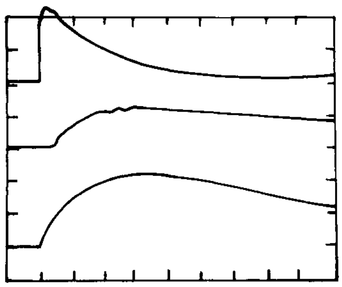


Fig. 7. Oscillograms from EMC test.
Upper curve: applied current pulse, 10 kA/div; 10 ms/div.
Middle curve: rotor speed 450 rpm/div; 10 ms/div.
Lower curve: voltage across EMC 1 V/div; 10 ms/div.

The effective series resistance represents ohmic losses in the rotors, ohmic losses at the stator/NaK/rotor interfaces, frictional losses at the bearings, fluid-dynamic (viscous) losses in the NaK, and MHD losses arising from the magnetic field in the NaK.[7,8]

If the ohmic losses were predominant, the voltage drop at current peak would have been in the range of 1.8 volts. This is not the case according to Fig. 7. It appears then that most of the losses are friction, fluid-dynamic and MHD. Friction losses at the bearing are proportional to the square of the rotational speed. Fluid-dynamic losses and MHD losses are proportional to the third power of the rotor surface velocity.[7,8] Therefore, these losses are the highest at the maximum speed of the rotor when the current is zero.

The EMC is completely flooded with NaK, and the NaK inside the EMC is under hydrostatic pressure because of the higher elevation of the NaK reservoir (Fig. 5). Therefore, the viscous and the MHD losses are minimized. It appears that friction at the bearings is the main source of losses.

The capacitance of the present model of the EMC is much higher than for practical application. The capacitance can be reduced by increasing the magnetic field, decreasing the density of the rotor material, as shown in eq. (2b), and also by connecting several modules in series. Our future work will focus attention on these problems.

Conclusions

Although the concept of the homopolar machine is not new (Faraday, 1831), our proposed application which is directed to energy transfer, is new. This application requires simpler design than those when the homopolar machine is used for energy storage or for power generation.

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